

BREMNER

Hydraulics of Culverts

Civil Engineering

B. S.

1912

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HYDRAULICS OF CULVERTS

BY

CHARLES WILLIAM BREMNER

THESIS

FOR THE

DEGREE OF BACHELOR OF SCIENCE

IN

CIVIL ENGINEERING

COLLEGE OF ENGINEERING

UNIVERSITY OF ILLINOIS

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COLLEGE OF ENGINEERING.

May 24, 1912

This is to certify that the thesis of CHARLES WILLIAM BREMNER entitled HYDRAULICS OF CULVERTS was prepared under my personal supervision; and I recommend that it be approved as meeting this part of the requirements for the degree of Bachelor of Science in Civil Engineering.

Melvin L. Enger
A. M. Talbot

Instructors in Charge.

Recommendation approved:

Ira O. Baker

Professor of Civil Engineering.

HYDRAULICS OF CULVERTS.

A culvert is an opening through a highway or railroad embankment to carry a small stream. Hydraulics of a culvert is the study of the laws of flow of water through the culvert. There are many kinds of culverts in use, some of which are pipe, arch, and box culverts. A box culvert, narrow with respect to height (6 in. x 4 ft.), has been used in the experimental work of this thesis. It was thought that this shape would allow better chance for observations with the rate of flow available, than one of more ordinary proportions.

There is very little known about the losses of head and the discharging capacity of culverts. The principles of the flow of water in long pipes and conduits are quite well established but they are not directly applicable to the flow in culverts. An investigation of the laws of discharge in culverts should therefore be of value.

Before going into this investigation it may be well to review the theoretical explanation of lost head. It is a well known fact that just after water enters into a culvert there is a decided drop in in the surface of the water and then a rise of the surface. The drop near the entrance is caused by entrance loss, velocity head, and friction loss. The friction loss, being so small for the short length considered, will be included in the entrance loss. An

equation in terms of effective heads will be used as follows:

$$h = h_1 + \frac{v_1^2}{2g} + h'$$

where h' is the lost entrance head and is equal to $e \frac{v_e^2}{2g}$.

Therefore transposing and substituting for h

$$h - h_1 = \frac{v_1^2}{2g} + e \frac{v_e^2}{2g}$$

or

$$D = \frac{v_1^2}{2g} + e \frac{v_e^2}{2g}$$

in which D is the lost head between the surface of the water before it enters the culvert and any section under consideration; v_e is taken at the entrance and e is the coefficient of entrance head; $\frac{v_1^2}{2g}$ is the amount of lost head in imparting velocity to the water

v being taken at the section considered. (See Fig. 1)

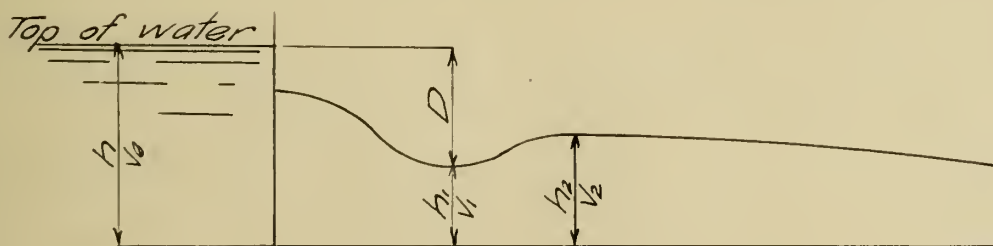


Fig. 1.

Since there have been no experiments performed on the hydraulics of culverts, it was a question as to the best method of procedure in getting data for these experiments. At first the Boneyard seemed to be the only available place where enough water could be

supplied to flow through the culvert, but the difficulty of the measurement and the control of the flow caused this plan to be abandoned. The proposed plan was to construct a culvert across the stream in such a manner that different sized openings and shapes could be studied, the wings of the culvert were to be built up of 2" x 8" board pile sheating, held in place by 4" x 4" posts, driven into the bed of the stream. After a close inspection of the banks of the stream and running levels the writer decided to build the culvert fifty feet west of the west line of the Mathews Avenue bridge, and a design for a simple wooden culvert to use for experimental work was made as shown in Fig.2. The culvert was to be about twenty feet long and open on the top, so as to obtain readings to the water surface. By this method the water could be backed up possibly to a four foot head and the depth regulated by a sluice gate through which the unnecessary water could be run out. The culverts to be installed were square, rectangular, and round diameters of four feet. The cost for the material and construction would have been rather expensive.

In the hydraulics laboratory the supply of water could be maintained constant by means of pumps until an experiment was finished, and then another rate of flow could be obtained. It seemed, therefore, to be the best place to make the experiments.

The apparatus, as shown in the picture, was set up according to the plans in Fig. 3. To obtain the quantity of water flowing through the culvert, vertical jets(8 inches and 10 inches in diameter)were used. The water fell into a catcher and ran off into a box in which two baffle boards were set, so as to lessen the splash and cause a more even flow into the mouth of

the culvert. The culvert was 13 1/2 ft. long and six inches wide. It would have been better to use a culvert 8 inches or a foot wide to obtain a steadier flow of water. In calculating the quantity of water used the formula $Q = ca\sqrt{2gh}$ was used. c is a constant value which is different for the different sizes of jets used. For the 8 inch jet $c = .65$, and for the 10 inch, $c = .68$. a is the area of the orifice in square feet. h is the height of the jet of water above the face of the orifice plate in feet, and g is the acceleration of gravity (32.2 ft. per second). A curve as shown in Plate A was plotted in which Q for any height of jet could be read directly for both the 8 inch and 10 inch nozzles.

Measurements of the surface of the water for various discharges were made by using a folding ruler and measuring from the top of culvert to the top of water. For the first 7 feet, the culvert top was 4 ft. above the bottom but from 7 1/2 ft. to the end the top of culvert was only 3' - 1 1/2" inches above the bottom of the culvert. Elevations were taken of the surface of the water before entering the culvert, and every half of a foot from the entrance to the end, - a set of elevations for each discharge. These measurements were first taken when the outlet was free and then an obstruction one foot deep was placed at the end so as to act the same as if water backed up the flow through the culvert. This caused a more steady flow and lessened the drop of water at the entrance considerably. The water came out of the end as shown in Fig. 4.

Experiments were also made with the entrance to culvert 2 ft., 1 1/2 ft., and 1 ft. deep. Readings were also taken with

backwater conditions with the 3 ft. entrance.

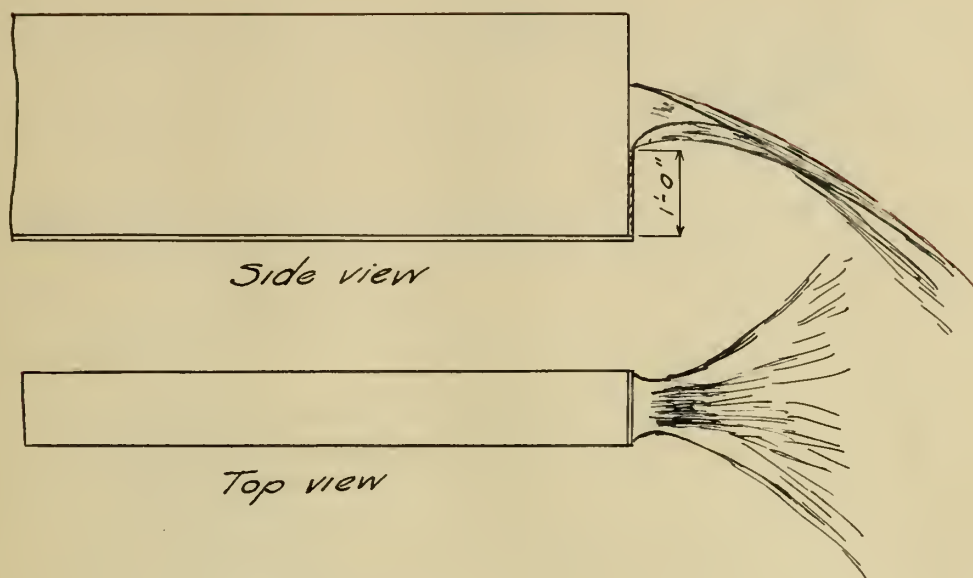


Fig. 4.

It was rather difficult to obtain readings for the 1 1/2 ft. and 1 ft. entrances as the water came through the opening with such velocity that the water foamed and splattered and the exact surface near the entrance could not be noted.

There were several errors which modified the results, and which caused the wide variation of the value of entrance coefficient, as shown in the tables. First, the leakage from cracks in the catcher and culvert was quite large and some water escaped by splashing over the edge of the box as it fell from the catcher. Second, the surface of the water was not quiet or even enough to obtain accurate readings of the water surface with the rule, and the variations in results are due to this error more than the others. Third, the height of the jet of water coming through the orifice could not be accurately determined, as the action of the pumping caused a slight pulsation of the jet. The reading was obtained by sighting across the top of the jet from one scale to

another as shown in Fig. 5. However, the error in figuring the discharge was slight, and this method of obtaining the quantity of water flowing proved very satisfactory.

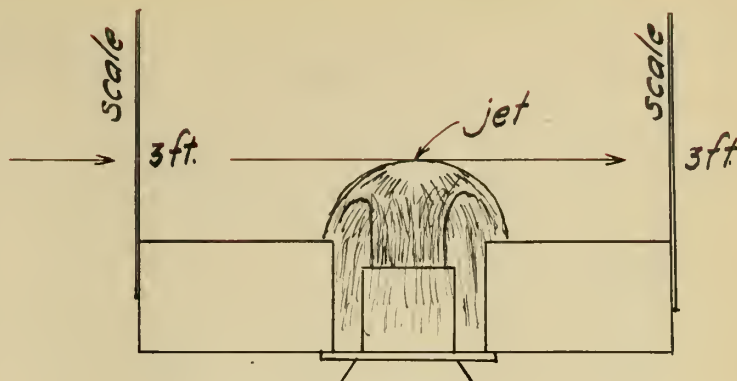


Fig. 5.

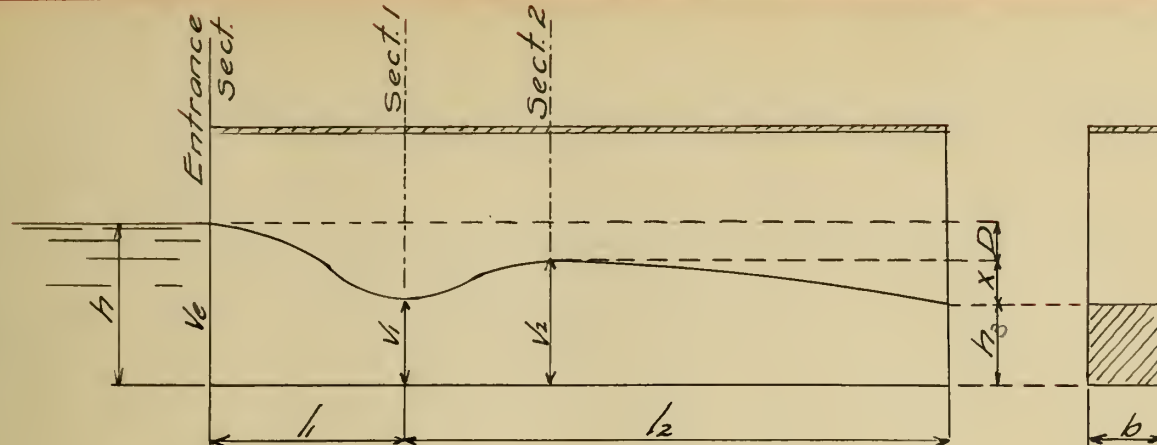
In figuring out the values of the coefficients e_1 and e_2 with respect to sections 1 and 2 respectively, the velocities were taken as the average at those sections and figured out from the formula $Q = av$ where Q = the discharge in cu. ft. per sec., a = the area in square feet for the section under consideration, and v is the velocity in feet per second at that section. Lack of time prevented Pitot tube readings to determine actual distribution of velocities in different cross sections of the culvert.

The entrance coefficients e_1 and e_2 seem to vary widely for the different conditions of discharge considered. As has been said before, this may be due to the error in determining elevation of the surface of the water. The average value of e_1 seems to be about one, and this value of e_1 is recommended for use.

Solution of Typical Problems.—The solutions of several problems which arise in the discussion of flow of water in culverts are given below.

PROBLEM I.

Given depth of back-water and rate of discharge in a level culvert not flowing full, to determine depth of headwater.



We have $Q = av$

a in this problem = bh

therefore $v_3 = \frac{Q}{bh}$

$v_2 = v_3$ approximately (except in long culverts)

From Chezy's formula

$$v_3 = c \sqrt{rs} = c \sqrt{\frac{bh}{b+2h} \cdot \frac{x}{l_2}}$$

$$v_3^2 = c^2 \frac{bh}{b+2h} \cdot \frac{x}{l_2}$$

$$x = \frac{v_3^2 l_2 (b+2h)}{c^2 bh} \quad (1)$$

Determine c from Kutter's formula using a value of n depending upon conditions. The value of x determined by equation (1) is too high because the value of v_3 is greater than the average velocity. If x is too large, a second solution may be made by using an average between v_2 and v_3 . The value of v_2 is $\frac{Q}{b(h+x)}$. A more nearly correct value of x may be determined by this solution.

Experiments show that the drop between entrance and section 2 can be approximately expressed by

$$D = e \frac{v_e^2}{2g} + \frac{v_2^2}{2g} \quad (2)$$

Taking $e = 1.00$ and $v_e = \frac{Q}{(h+x+D)b}$



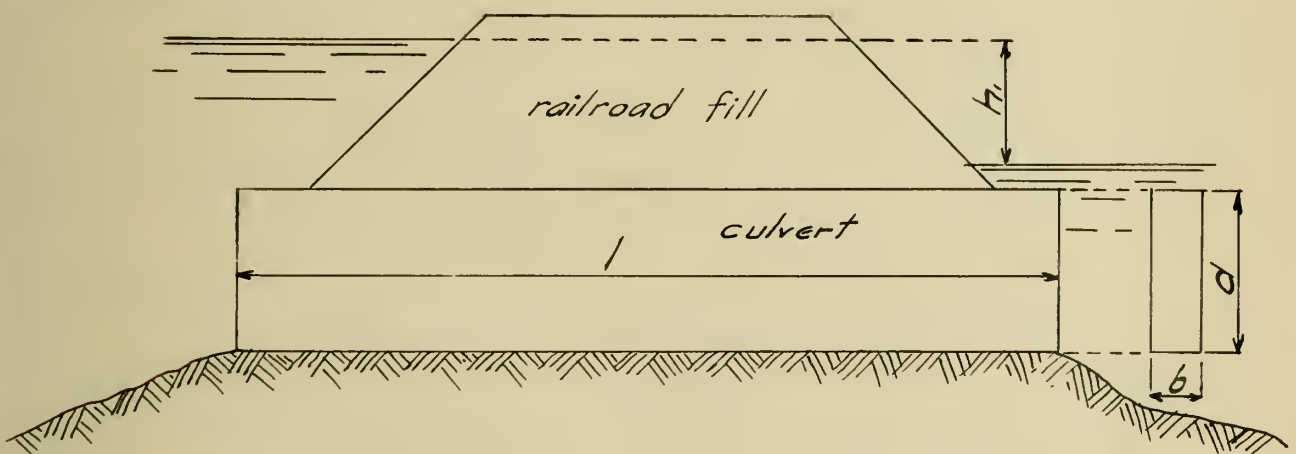
A value of D can be formed by trial satisfying equation (2) and the condition for e .

Since this gives the values of the heads used to make up the depth of headwater (H), the equation is

$$H = h + x + d. \quad (7)$$

PROBLEM 2.

Backwater level with roof of culvert, or higher, to determine the depth of head-water above backwater with a given rate of discharge.



$$v = \frac{Q}{bd}$$

$$v = c \sqrt{rs} = c \sqrt{\frac{bd}{2(b+d)} \cdot \frac{h'}{1}}$$

Find e from Kutter's formula using a value of n depending upon conditions. h' is the velocity lost head.

$$\frac{Q}{bd} = c \sqrt{\frac{bd}{2(b+d)} \cdot \frac{h'}{1}}$$

$$h' = \frac{2Q^2 l (b + d)}{c^2 b^3 d^3} \quad (1)$$

The entrance loss $h_e = e \frac{v_e^2}{2g}$

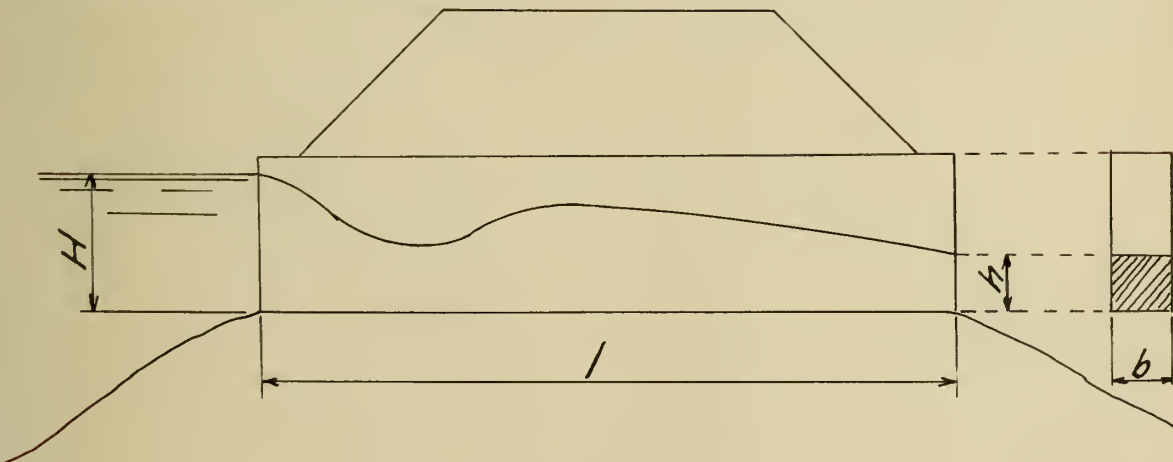
$$v_e = v$$

$$h_e = e \frac{v_e^2}{2g} = e \frac{v^2}{2g} = e \frac{Q^2}{2b^2 d^2 g} \quad (2)$$

$$\text{and } h_f = h' + h_e \quad (3)$$

PROBLEM 3.

Given the elevations of head water and backwater and size of culvert to determine rate of flow, both headwater and backwater being below top of culvert.



This problem must be solved by trial.

To determine Q approximately substitute in Chezy's formula to determine average velocity. Use

$$s = \frac{H - h}{l}$$

and

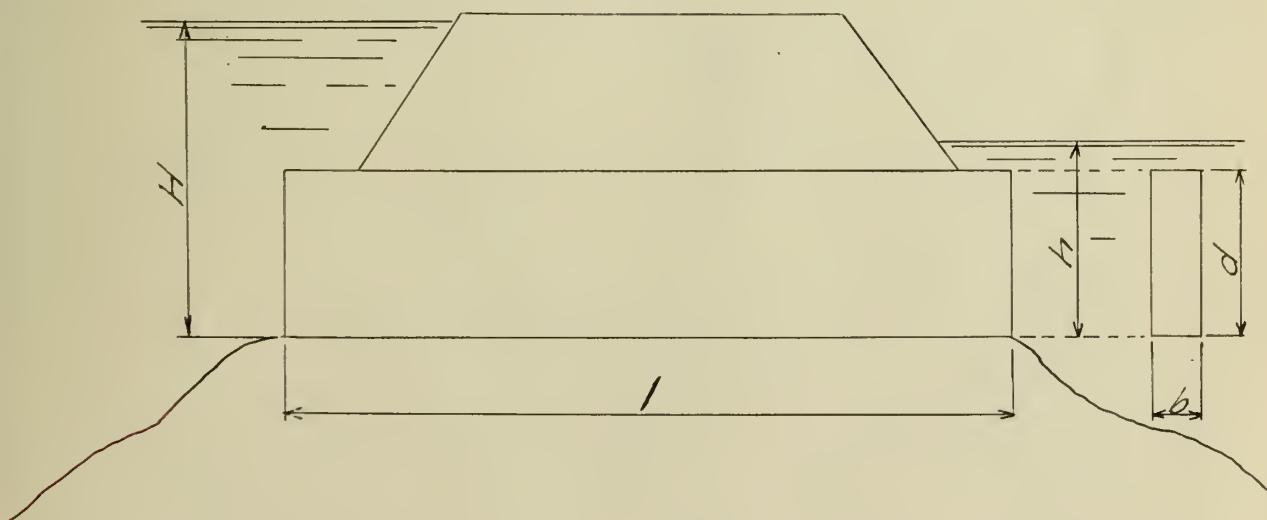
$$r = \frac{\frac{H + h}{2} b}{b + H + h} = \frac{(H + h) b}{2 (b + H + h)}$$

$$Q = av = \left(\frac{H + h}{2} b \right) v$$

With this value of Q solve as in Problem I and determine difference of elevation of headwater and backwater. If this differs from $H - h$ and the value of Q may be assumed and the solution again gone through until the actual and computed values are in agreement.

PROBLEM 4.

Given the elevations of headwater and backwater and size of culvert to determine rate of flow, both headwater and backwater above top of culvert.



$$v = c \sqrt{rs} = c \sqrt{r \frac{h'}{l}}$$

$$\frac{v^2}{c^2} = r \frac{h'}{l}$$

Therefore,

$$h' = \frac{v^2 l}{c^2 r}$$

$$H - h = e \frac{v^2}{2g} + \frac{v^2 l}{c^2 r} + \frac{v^2}{2g}$$

Take $e = 1$,

$$H - h = \frac{v^2}{2g} \left(1 + \frac{2gl}{c^2 r} + 1 \right) = \frac{v^2}{2g} \left(2 + \frac{2gl}{c^2 r} \right)$$

Therefore,

$$v = \sqrt{\frac{2g(H - h)}{2 + \frac{2gl}{c^2 r}}}$$

And

$$Q = av = bd \sqrt{\frac{2g(H - h)}{2 + \frac{2gl}{c^2 r}}}$$

C.W.B.

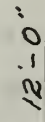


Fig. 2

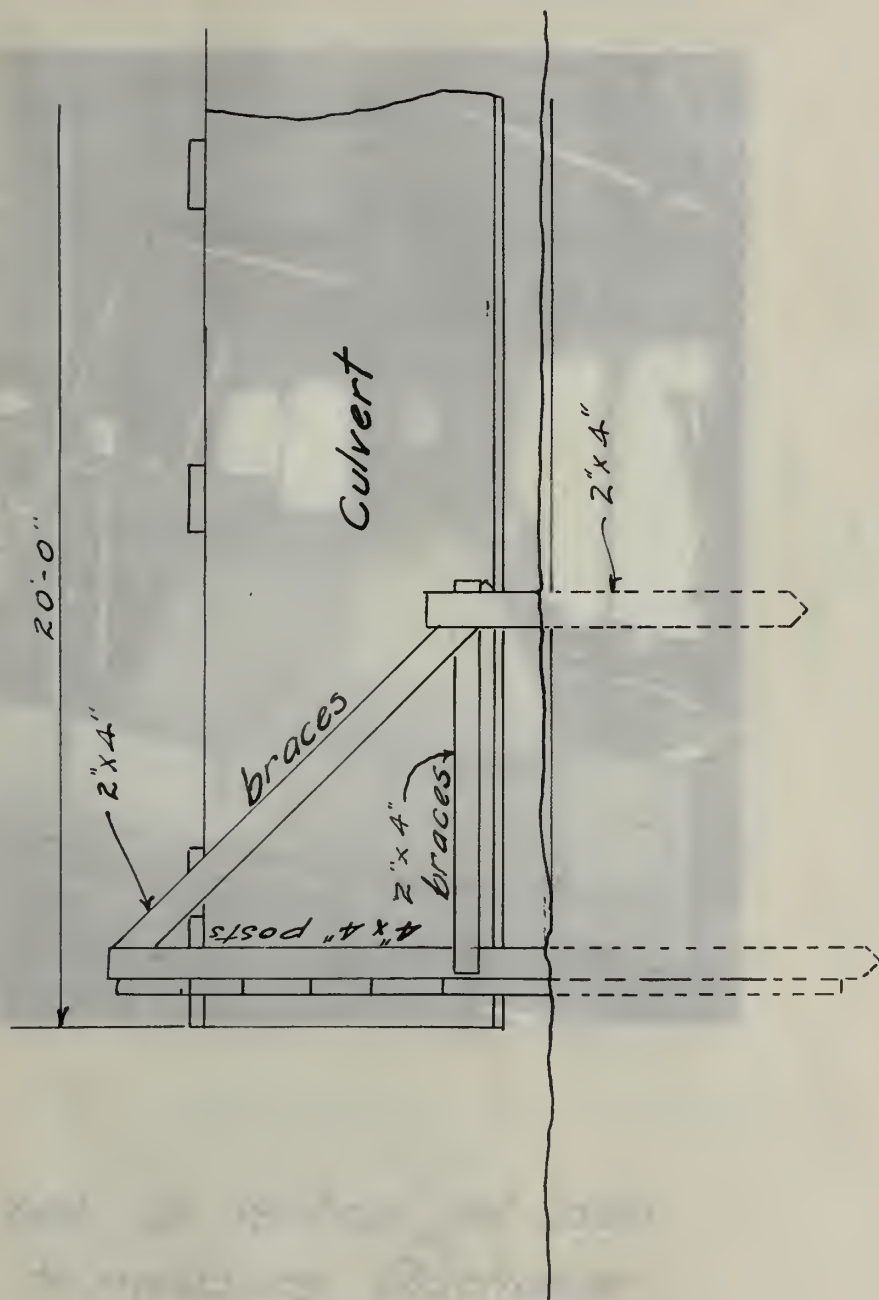
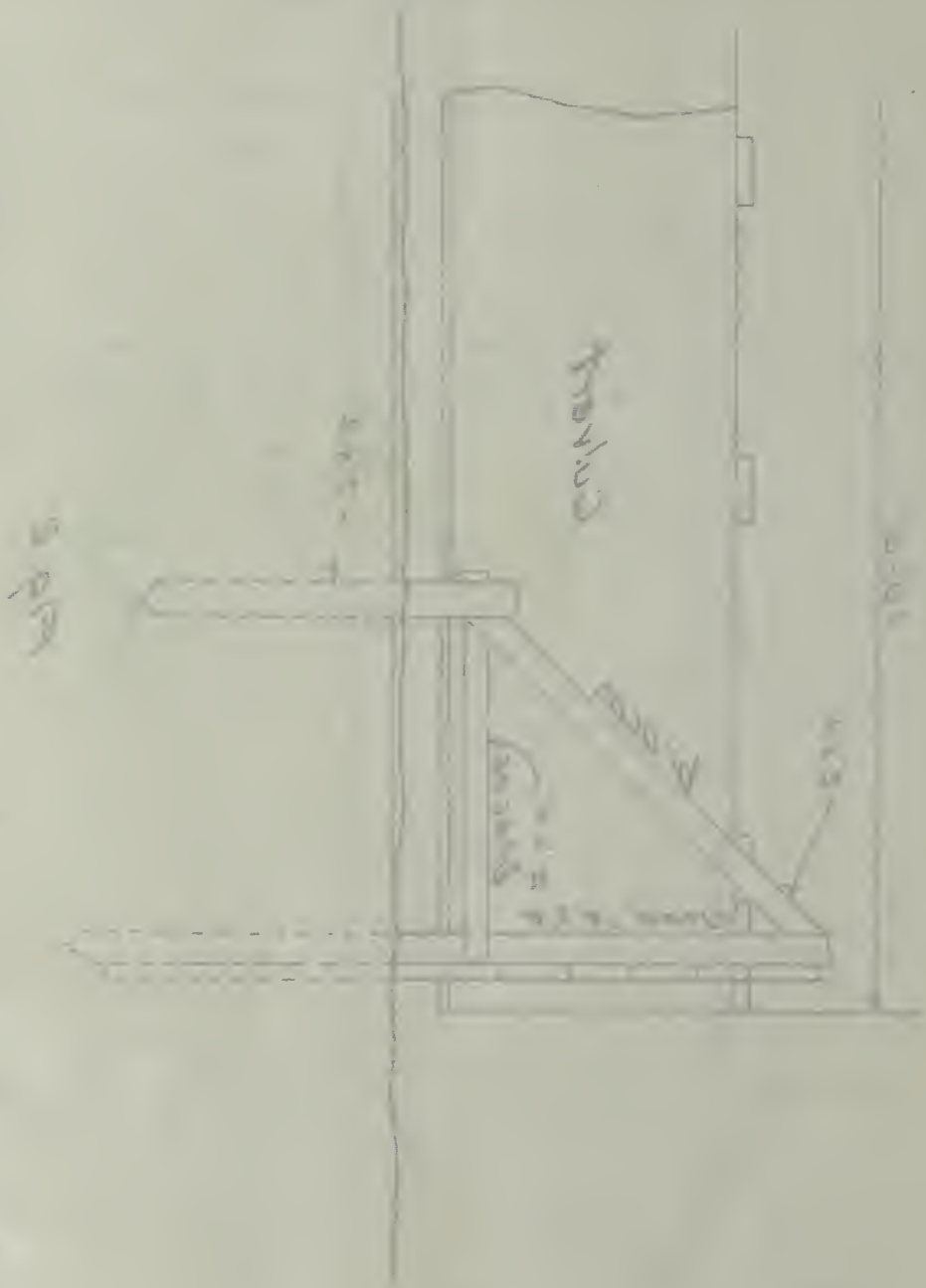


Fig. 2





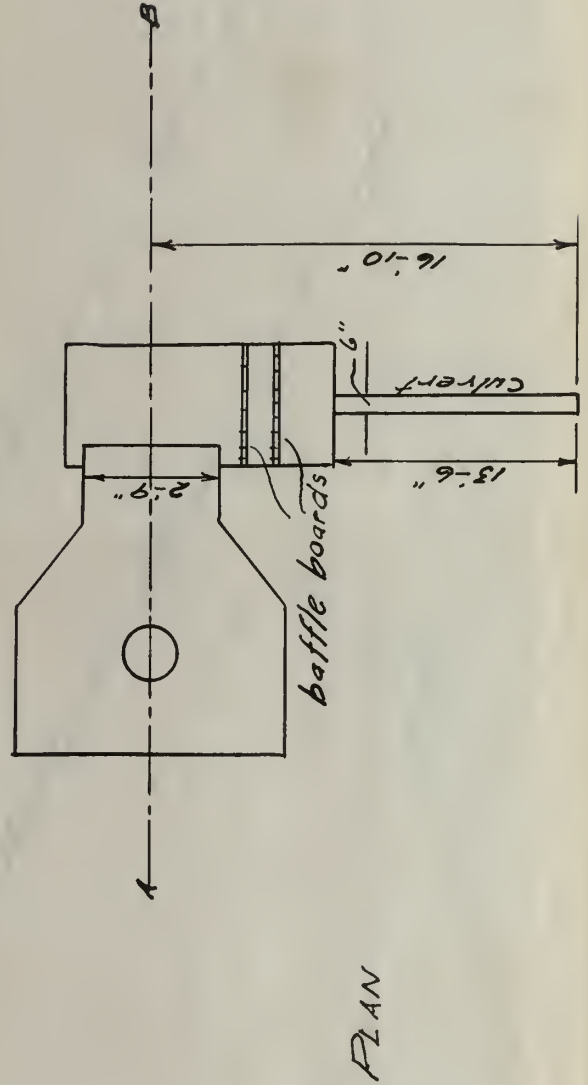
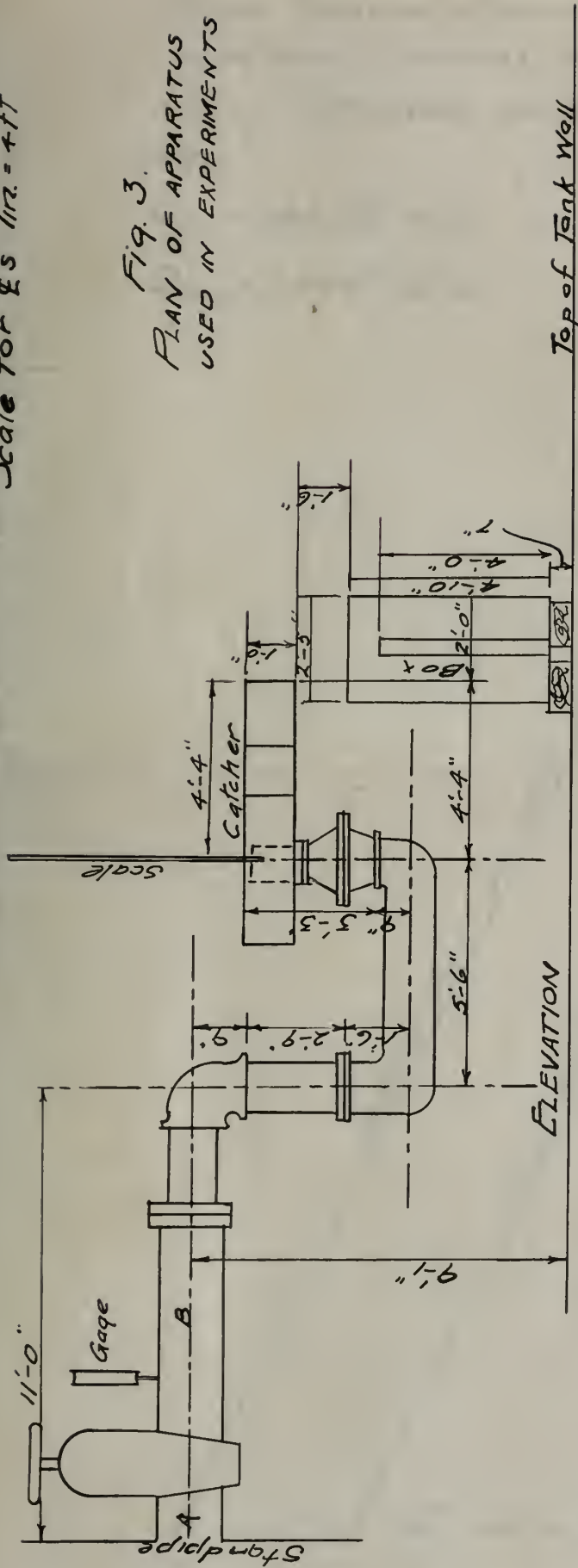
*View of Vertical jet used
to measure Discharge
of Culvert*



View of Culvert-free outlet.

Scale for $\frac{1}{2}$ in. = 1 ft

Fig. 3.
PLAN OF APPARATUS
USED IN EXPERIMENTS



$$2500 = 500 \times 5 = 100 \times 25 = 20 \times 125 = 4 \times 625$$

PLATE A.
 GRAPH SHOWING DISCHARGES
 UNDER VARIOUS HEADS OF 8"
 AND 10" ORIFICES ON A 12"
 PIPE.

$$Q_{8 \text{ in.}} = 1.82 \sqrt{H} \text{ c.f.s.}$$

$$Q_{10 \text{ in.}} = 2.89 \sqrt{H} \text{ c.f.s.}$$

Height of jet (H) in feet

8 in. orifice on 12 in. pipe.

10 in. orifice on 12 in. pipe.

Q in c.f.s.

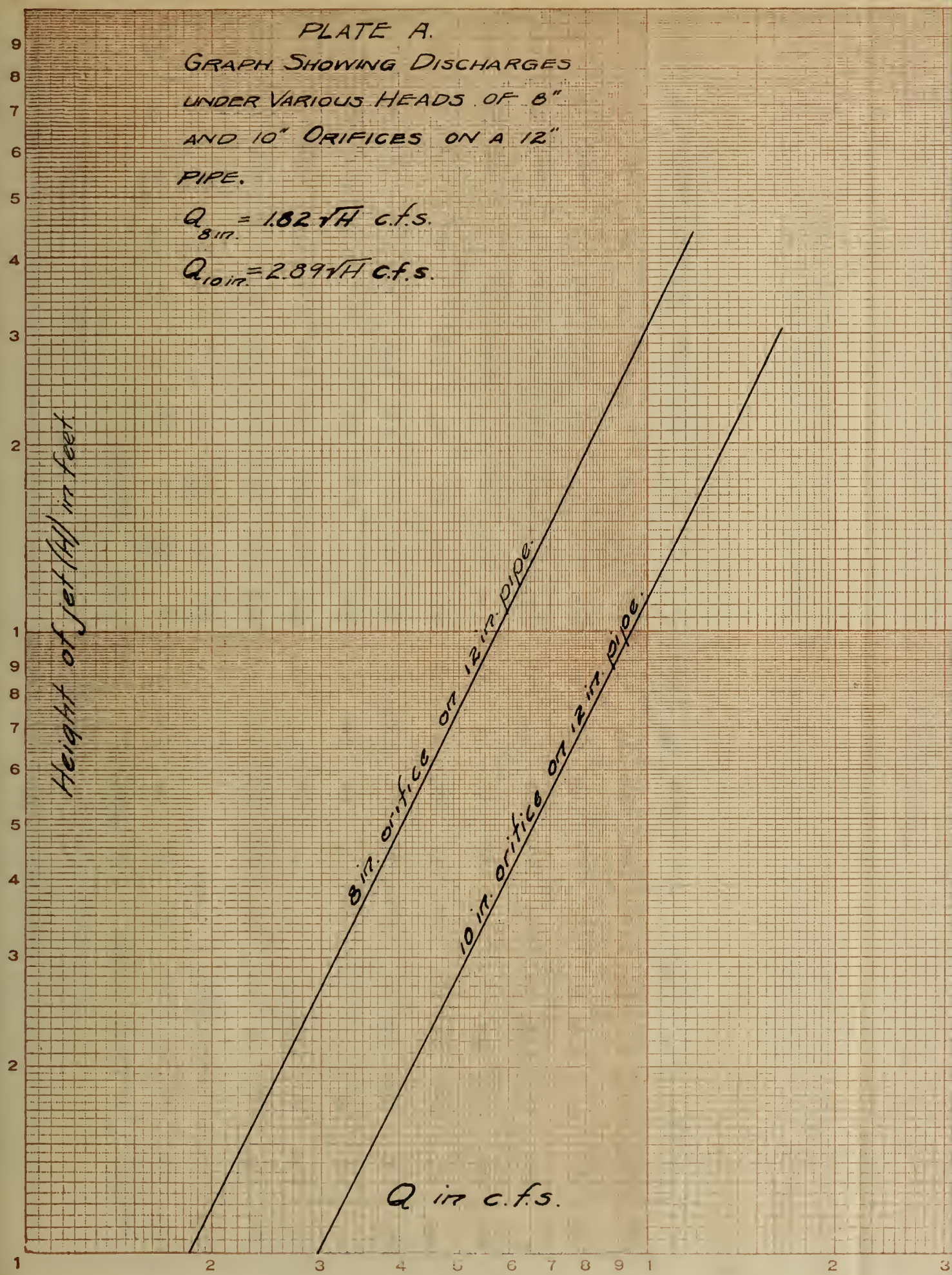


Table 1.

Culvert is 6 ft. wide - 4 ft. deep														opened					outlet.				
Ht.	Q	A _e	A ₁	A ₂	h ₁	h ₂	h	h-h ₁	h-h ₂	V _e	$\frac{V_e^2}{2g}$	V ₁	$\frac{V_1^2}{2g}$	V ₂	$\frac{V_2^2}{2g}$	$\frac{V_2^2}{2g}$	e ₁	e ₂					
ft.	cfs	square	feet.	feet.	feet.	feet.	feet.	feet.	feet.	ft./sec.	ft.	ft./sec.	ft.	ft./sec.	ft./sec.	ft.							
1.07	1.85	.625	4.0	.538	80	1.075	1.25	45	.175	296	.136	4.62	.332	3.44	.183	.118	.008	.87	.059				
1.7	2.35	.75	4.75	.63	.95	1.25	1.50	.55	.25	314	.152	4.95	.380	3.74	.216	.170	.034	1.12	.224				
2.1	2.6	.80	.50	.69	1.00	1.38	1.60	.60	.22	325	.164	6.2	.42	3.77	.22	.180	.00	1.10	.00				
2.5	2.85	.825	.537	.72	1.075	1.43	1.65	.575	.22	346	.185	5.3	436	3.96	.242	.139	.022	.75	.119				
2.95	3.1	.925	.563	.76	1.125	1.53	1.85	.725	.32	335	.174	5.5	47	4.08	.257	.255	.063	1.46	.362				
3.05	3.15	.90	.55	.75	1.1	1.50	1.85	.75	.35	350	.190	5.73	.51	4.20	.272	.24	.078	1.26	.410				
3.6	3.45	.95	.575	.78	1.15	1.55	1.90	.75	.35	363	.204	6.0	.56	4.42	.302	.19	.048	.93	.235				
3.8	3.50	.95	.575	.80	1.15	1.60	1.90	.75	.30	369	.211	6.1	.58	4.38	.296	.17	.044	.805	.018				
4.0	3.65	1.00	.60	.83	1.2	1.65	2.00	.80	.35	365	.207	6.08	.571	4.4	.30	.229	.05	1.11	.24				
4.6	3.9	1.05	.60	.838	1.2	1.675	2.10	.90	.425	372	.214	6.5	.655	4.65	.334	.245	.091	1.14	.42				

Table 4

Ht.	Q	A _E	A ₁	A ₂	h ₁	h ₂	h	h-h ₁	h-h ₂	V ₆	$\frac{V_6^2}{2g}$	V ₁	$\frac{V_1^2}{2g}$	V ₂	$\frac{V_2^2}{2g}$	$\frac{h-h_1}{2g}$	$\frac{h-h_2}{2g}$	e ₁	e ₂
.95	2.9	.75	.635	.675	1.27	1.35	1.75	.48	.40	3.86	.231	4.57	.323	4.3	.285	.157	.115	.68	.50
1.15	3.18	.75	.675	.725	1.35	1.45	1.87	.52	.42	4.24	.278	4.7	.342	4.38	.296	.178	.124	.64	.446
1.4	3.5	.75	.70	.785	1.4	1.57	2.04	.64	.47	4.67	.337	5.00	.386	4.46	.308	.254	.162	.75	.48
1.75	3.9	.75	.75	.875	1.5	1.75	2.05	.55	.30	5.20	.418	5.00	.418	4.46	.308	.132	-.008	.316	-.019
2.15	4.45	.75	.75	.925	1.5	1.85	2.45	.95	.60	5.93	.544	5.93	.509	4.81	.358	.441	.242	.81	.445

Culvert is 6 ft. wide - 1 ft. 6 in. deep. 0 free outlet.

Table 5

Ht.	Q	A _E	A ₁	A ₂	h ₁	h ₂	h	h-h ₁	h-h ₂	V ₆	$\frac{V_6^2}{2g}$	V ₁	$\frac{V_1^2}{2g}$	V ₂	$\frac{V_2^2}{2g}$	$\frac{h-h_1}{2g}$	$\frac{h-h_2}{2g}$	e ₁	e ₂
.48	2.06	.50	.425	.50	.85	1.00	1.2	.35	.2	4.12	.262	4.85	.364	4.12	.262	-.014	-.062	-.053	-.236
.71	2.51	.50	.475	.60	.95	1.2	1.3	.35	.1	5.02	.389	5.28	.433	4.2	.273	-.083	-.173	-.21	-.445

Culvert is 6 ft. wide - 1 ft. deep. free outlet.

Data for Plates 1 to 9

Measurements taken from 4 ft. above bottom of culvert to water surface.
From 7½ ft. to end of culvert measurements taken 3-1½" above bottom.

Ht. = height of jet $Q = 182 \frac{144}{10} \text{ c.f.s.}$ $Q = 289 \frac{144}{10} \text{ c.f.s.}$ $L = \text{water surface before entrance.}$

Plate 1 - 8 in. nozzle

Ht. ft.	Q c.f.s.	E inches	0	½	1	1½	2	2½	3	3½	4	4½	5	5½	6	6½	7	7½	8	9	10	11	12	13	14
105	185		33	35½	38½	36½	35	35½	36	36½	36½	36½	36½	36½	36½	37	37	26½	26½						
36	345		25	28	32	34	34½	34½	34	32½	31½	29½	29½	31	32½	32½	33	23	23	22½	22½	23	24	25½	
46	390		23	26	31	32½	33	33½	33½	32½	31½	30	28½	28	29	30	30½	21	22	22½	22½	22½	23½	24½	
105	185		24	25½	24½	24½	24½	24½	24½								24½			14½			14½	15½	16

Plate 2 - 8 in. nozzle

Ht. ft.	Q c.f.s.	E inches	0	½	1	1½	2	2½	3	3½	4	4½	5	5½	6	6½	7	7½	8	9	10	11	12	13	14
170	235		30	32½	36	36½	34½	33	33	34	34½	35	35	35	34½	34½	34½	24½	24½						
295	310		26	29	33	34½	34½	34	32½	30½	29½	31	32	32½	33	33½	33½	22½	22½						
40	365		24	25½	50	32½	33½	33½	33½	32½	31½	29	28½	29½	29½	31	32	21½	22½						
40	365		17	20	20½	18½	18½	18	18								18½			8			8½	10	11½

B = backwater of 1 ft. at outlet end.

Plate 3 - 8 in nozzle

Ht	Q	F	0	$\frac{1}{2}$	1	$1\frac{1}{2}$	2	$2\frac{1}{2}$	3	$3\frac{1}{2}$	4	$4\frac{1}{2}$	5	$5\frac{1}{2}$	6	$6\frac{1}{2}$	7	$7\frac{1}{2}$	8	9	10	11	12	13	14
R.1	2.6		29	$5\frac{1}{2}$	34	36	$34\frac{1}{2}$	32	$31\frac{1}{2}$	$31\frac{1}{2}$	$32\frac{1}{2}$	$33\frac{1}{2}$	$33\frac{3}{4}$	$34\frac{1}{2}$	$34\frac{1}{2}$	34	$33\frac{3}{4}$	23	$23\frac{3}{4}$		25		26	$27\frac{1}{2}$	
2.5	2.85		28	31	35	35	35	$33\frac{1}{2}$	$31\frac{1}{2}$	31	$31\frac{1}{2}$	$32\frac{1}{2}$	33	$33\frac{1}{2}$	$33\frac{3}{4}$	$33\frac{1}{2}$	$33\frac{1}{4}$	$22\frac{1}{2}$	$22\frac{1}{4}$		24		$25\frac{1}{2}$	27	
2.1	2.60		$21\frac{1}{4}$	$22\frac{3}{4}$	$23\frac{1}{4}$	22	$21\frac{1}{2}$	$21\frac{1}{2}$	$21\frac{1}{2}$							$21\frac{3}{4}$					$11\frac{1}{2}$		12	$12\frac{3}{4}$	$13\frac{3}{4}$
2.6	2.91		20	22	$21\frac{1}{2}$	$20\frac{3}{4}$	$20\frac{1}{2}$	$20\frac{1}{2}$	$20\frac{3}{4}$								21				$10\frac{3}{4}$		$11\frac{1}{4}$	$12\frac{1}{4}$	$13\frac{1}{4}$

Plate 4 - 8 in nozzle

Ht	Q	F	0	$\frac{1}{2}$	1	$1\frac{1}{2}$	2	$2\frac{1}{2}$	3	$3\frac{1}{2}$	4	$4\frac{1}{2}$	5	$5\frac{1}{2}$	6	$6\frac{1}{2}$	7	$7\frac{1}{2}$	8	9	10	11	12	13	14
3.05	3.15		26	29	33	34	$34\frac{1}{2}$	$34\frac{3}{4}$	$33\frac{1}{2}$	32	$30\frac{1}{4}$	$30\frac{1}{4}$	31	$32\frac{1}{4}$	$32\frac{3}{4}$	$33\frac{1}{2}$	$33\frac{1}{2}$	$23\frac{1}{4}$	$22\frac{3}{4}$		$22\frac{1}{2}$		22	$24\frac{1}{2}$	
3.80	3.50		25	$27\frac{1}{4}$	$31\frac{1}{4}$	$33\frac{1}{2}$	34	34	34	33	$32\frac{1}{2}$	$29\frac{1}{2}$	$28\frac{3}{4}$	30	$30\frac{1}{2}$	$31\frac{1}{4}$	32	$22\frac{1}{4}$	$22\frac{1}{4}$		$22\frac{3}{4}$	23	$23\frac{3}{4}$	25	
3.05	3.15		19	21	$21\frac{1}{4}$	20	$19\frac{1}{2}$	$19\frac{1}{2}$	$19\frac{1}{2}$								20				$9\frac{1}{2}$		10	$11\frac{1}{2}$	$12\frac{1}{2}$

Plate 5 - 10 in nozzle

|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|

Plate 6-10 in. nozzle.

Ht	Q	E	0	$\frac{1}{2}$	1	$1\frac{1}{2}$	2	$2\frac{1}{2}$	3	$3\frac{1}{2}$	4	$4\frac{1}{2}$	5	$5\frac{1}{2}$	6	$6\frac{1}{2}$	7	$7\frac{1}{2}$	8	9	10	11	12	13	14
105	303	$18\frac{1}{2}$	23	$22\frac{1}{2}$	22	$21\frac{1}{2}$	$21\frac{1}{2}$	$21\frac{1}{2}$	$21\frac{1}{2}$	$21\frac{3}{4}$	$21\frac{3}{4}$											12	$13\frac{1}{4}$	$14\frac{1}{4}$	
2.7	485	$16\frac{1}{2}$	24	24	26	28	$28\frac{1}{4}$	$28\frac{1}{4}$	28	$27\frac{3}{4}$	27	$26\frac{1}{2}$	25	25	$26\frac{1}{4}$	$26\frac{1}{2}$			18		20		$21\frac{1}{4}$	$22\frac{1}{2}$	$23\frac{1}{2}$

Plate 7-10 in. nozzle

48	2.06	33½	36	36	38	36½	36	36½	36½	36½	36½	36½	36½	37								27¾	28½	29½	30½
71	2.51	30½	36		36½	34	34½	34¾	35	35	35	34¾	35	35								26	27½	28½	29½

Plate 8-10 in. nozzle.

215	445	18½	30		29½	27½	26½	25¾	26	27	28	28	28½	30								19½	21½	23½	24½
14	3.5	25½	30	29	30¾	29½	29½	29½	30	31	31½										22½	24	25½	26¾	
95	2.9	27	30	30½	32¾	32	32	32	32½	32½	33										24½	25½	27	28	

Plate 9-10 in. nozzle.

1.75	3.9	20½	30		28½	27½	27	27½	27¾	29¼	30											20½	22½	24½	25½
1.15	3.18	25½	30	30	31¾	31½	30½	30¾	31	31¼	31¾	31¾											24½	26½	27½

Height of Water in feet

Plate 1.
Profile of Water Surface
in a culvert 6 in wide by 4 ft deep
by 13½ ft long for various dis-
charges. Free outlet and
backwater end.

backwater of 1'-0"

$Q = 3.9 \text{ cfs.}$

3.46

1.85

Length of Culvert in feet

0 ½ 1 1½ 2 2½ 3 3½ 4 4½ 5 5½ 6 6½ 7 7½ 8 9 10 11 12 13 14

Plate 2.
Profile of Water Surface in a
culvert 617. wide by 4 ft deep
by 13½ ft. long for various
discharges.

Height of Water in feet

backwater of 1'-0"

Q = 3.6 cfs.



Length of culvert in feet.

Plate 3.
 Profile of Water Surface in
 a culvert 6 in wide by 4 ft deep
 by $13\frac{1}{2}$ ft long for various
 discharges.

Depth in feet.

$Q = 2.91 \text{ c.f.s.}$

back water of 1'-0"

2.6

2.85

2.6

Length in ft.

Plate 4.

Profile of Water Surface in
a culvert 6 in. wide by 4 ft deep
by $13\frac{1}{2}$ ft long for various dis-
charges.

Depth in ft.

$Q = 3.15 \text{ c.f.s.}$

backwater of 1'-0"

3.5

3.15

Length in feet.

0 1 2 3 4 5 6 7 8 9 10 11 12 13



Plate 5.
 Profile of Water Surface in
 a culvert 6 in. wide by 2 ft. deep
 by $13\frac{1}{2}$ ft long for various dis-
 charges.

Depth in feet

4.0

3.85

$Q = 3.85$ c.f.s.

backwater of 1'-0"

5.1

4.4

2.58

3.8

2.58

backwater of 1'-0"

5.1

4.4

3.8

1.0

0

1

2

3

4

5

6

7

8

9

10

11

12

13

Length in feet

Plate 6.
 Profile of Water Surface in
 a culvert 6 ft. wide by 2 ft. deep
 by $13\frac{1}{2}$ ft. long for various
 discharges.

40

30

4.85
 3.03

20

10

0

Depth in feet

$Q = 3.03 \text{ c.f.s.}$

backwater of 1'-0"

4.85

13

12

11

10

9

8

7

6

5

4

3

2

1

Length in feet

Plate 7.
 Profile of Water Surface in
 a culvert 617 wide by 1.0 ft
 deep by 13½ ft long for var-
 ious discharges.

Depth in ft.

2.51
 2.06

$Q = 2.51 \text{ c.f.s.}$

2.06

0 1 2 3 4 5 6 7 8 9 10 11 12 13

Length in feet

Plate 8.

Profile of Water Surface in
a culvert 6 in wide by 1'-6"
deep by 13½ ft long for var-
ious discharges.

Height of Water in feet

$Q = 4.45 \text{ cfs.}$

3.5

2.9

Length in feet

4.0

3.0

2.0

1.0

0

4.45

3.5

2.9

13

12

11

10

9

8

7

6

5

4

3

2

1

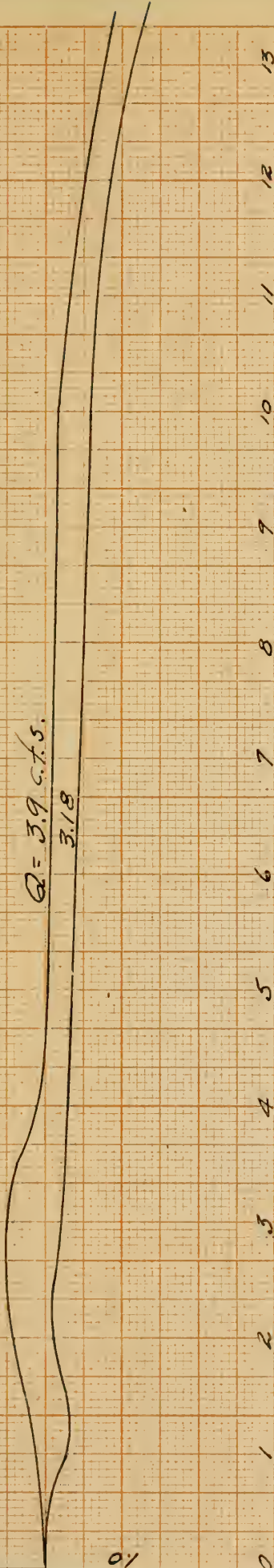
Plate 9.
 Profile of Water Surface in
 a culvert 6 in wide by 1 ft.
 6 in deep by 13½ ft. long for
 various discharges.

Depth in feet.

39
 318

$Q = 3.9$ c.f.s.

3.18

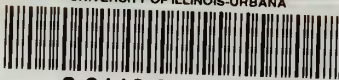


Length 117 feet.





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